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Physical Conditions in Lyman Break Galaxies Derived From Rest-Frame UV Spectra

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Abstract. We present the results of detailed studies of the astrophysical conditions in $z \sim 3$ Lyman Break Galaxies (LBGs), placing particular emphasis on what is learned from LBG rest frame UV spectra. By drawing from our database of ~ 1000 spectra, and constructing higher S/N composite spectra from galaxies grouped according to properties such as luminosity, extinction, morphology, and environment, we can show how the rest-frame UV spectroscopic properties systematically depend on other galaxy properties. Such information is crucial to understanding the detailed nature of LBGs, and their impact on the surrounding IGM.

1. Introduction

Until now, Lyman Break Galaxy (LBG) rest-frame UV spectra have been primarily used to measure redshifts. The measured redshifts confirm the high-redshift nature of galaxy candidates selected by their distinctive broadband optical colors (Steidel et al. 1996); enable the study of the spatial clustering of these galaxies (Adelberger et al. 1998); and, when combined with the apparent magnitudes and colors of LBGs, can be used to construct the rest-frame UV luminosity function and UV luminosity density at $z \sim 3$ (Steidel et al. 1999).

2. LBG Spectra

2.1. A Special Case: MS1512-cB58

One notable exception is the galaxy MS1512-cB58, a LBG at $z = 2.73$, discovered serendipitously by Yee et al. (1996) during the CNOC cluster redshift survey. cB58 has an apparent V magnitude of 20.6, due to lensing by a foreground cluster at $z = 0.37$, which boosts its apparent luminosity by about a factor of ~ 30 (Seitz et al. 1998). Due to the incredibly bright nature of cB58, a wealth of information has been extracted from medium-resolution ($R \simeq 5000$) studies of its rest-frame UV spectrum (Pettini et al. 2000, 2001). The velocity profiles of low and high-ionization interstellar metal absorption features have been characterized in detail; the weakest interstellar metal transitions have been used together with the damped Lyman-α absorption profile to determine the abundance pattern in cB58 (an α/Fe enhancement indicative of a young stellar population, and an abundance of $\sim 2/5 Z_{\odot}$ for the α elements); CIV and SIV P-Cygni stellar wind profiles have been used as independent probes of the stellar population and metallicity of cB58; weak stellar absorption features have been used to precisely measure the systemic velocity of the stars in cB58, relative to which the redshifts of Lyman α emission and interstellar absorption indicate offsets of several hundred km s^{-1}; finally, the strengths of the strongest interstellar absorption features (which have zero transmission at line center) have been used to infer a high covering fraction of absorbing material, through which negligible Lyman continuum emission can escape (Heckman et al. 2001).

2.2. Typical LBG Spectra

In stark contrast to the spectra of cB58, the 12.5Å resolution spectra obtained for unlensed LBGs ($R_{AB} = 23 - 25.5$) after 1.5 hours of integration with the Keck telescopes' Low Resolution Imaging Spectrometer (Oke et al. 1995) typically have signal-to-noise ratios of only a few, and therefore do not allow for the same type of detailed study on an individual basis. The only features visible in even the best spectra are Lyman α (in emission, absorption, or both), and the strongest interstellar absorption features, whose saturated equivalent widths are indicative of some combination of velocity widths and covering factor, but not abundance measures.

2.3. Composite LBG spectra

While individual LBG spectra provide limited information, our group has assembled a database of almost 1000 spectra of $z \geq 2$ galaxies over the past five years. Subsamples of galaxies can be drawn from the database with specific criteria, and used to construct higher S/N composite spectra. For example, a composite spectrum constructed from 29 LBGs at $\langle z \rangle = 3.4 \pm 0.09$ indicates significant positive flux bluewards of the Lyman cutoff at 912 Å (Steidel, Pettini, & Adelberger 2001). If this composite spectrum is taken to be representative of LBGs at $z \sim 3$, then the LBG contribution to the ionizing background at $z \sim 3$ could exceed that of QSOs at similar redshifts by as much as a factor of 5. It should be noted that this composite spectrum inhabits an extreme of LBG UV spectral parameter space, with strong Lyman α emission, a blue UV continuum slope, and interstellar absorption lines whose equivalent widths are roughly half the strength of those seen in cB58. Also, separate composite spectra constructed for 16 "young" ($t \leq 35$ Myr) and 16 "old" ($t \sim 1$ Gyr) LBGs, (whose stellar population parameters were determined from optical/IR photometry) exhibited systematic differences. The "old" spectrum had much stronger Lyman α emission, while the "young" spectrum had stronger interstellar absorption lines (indicating larger velocity widths or covering fraction of gas), and more pronounced P-Cygni high-ionization stellar wind features (Shapley et al. 2001).

3. Preliminary Results

Building on the above pilot studies which included composite LBG rest-frame UV spectra, we are now undertaking a systematic analysis of our entire database of spectra. These spectra primarily probe outflowing material which is being propelled by the mechanical energy input from active star-formation. In order to study the physical parameters of these outflows, we will determine how line strengths and kinematics vary in composite spectra constructed along sequences of properties such as UV-luminosity and color, bolometric luminosity, morphology (from HST), redshift, and Lyman α profile.

3.1. Lyman α vs. Reddening, Equivalent Widths, and Kinematics

As a first step, we have divided our sample according to a crude classification of Lyman α profile, and see intriguing variations in the resulting composite spectra. Based on the result of Steidel et al. 2000 that the distribution of LBG rest-frame Lyman α equivalent widths has a median of 0 Å and ranges from -100 Å to 100 Å, we divide galaxies into Lyman α "emission", "emission/absorption", and "absorption" subsamples. Figure 1 shows the resulting composite spectra, each of which contains more than 200 galaxies, and has a S/N per pixel of ~ 25.

We find that the UV continuum shape becomes systematically redder with increasing Lyman α absorption strength, indicating that both the UV continuum and Lyman α photons are affected by dust extinction, and providing information about the dust-gas geometry in LBGs. We also find that the equivalent widths of low-ionization interstellar features of SiII, OI, CII, FeII, and AlII, associated with the neutral ISM, increase with larger Lyman α absorption strength. As stated above, these equivalent widths are not indicative of abundances, but rather velocity widths, and possibly ISM covering factor. Therefore, the larger equivalent widths associated with the "absorption" spectrum indicate a larger velocity field, or possibly an ISM which is more opaque to ionizing radiation. We note that the spectrum of cB58 most closely resembles that of the composite "absorption" spectrum, whereas the composite spectrum used to measure the LBG Lyman continuum leakage has Lyman α emission and metal absorption strengths which are similar to that of the "emission" composite spectrum. Finally, kinematic properties of LBG outflows seem to depend on the Lyman α profile. The mean rest-frame velocity offset between Lyman α emission and interstellar absorption lines is $\Delta v = 630$ km^{-1}s ($\Delta z = 0.008$), however, the velocity offset decreases with increasing Lyman α emission strength. We have yet to determine whether this trend is dominated by ISM geometry, or evolutionary effects.

4. Conclusions and Future Work

Rapid star-formation has a profound effect on the ISM of LBGs, as seen in the large absorption equivalent widths and significant velocity offsets between rest-frame UV emission and absorption features. The effects of star-formation also extend to the surrounding inter-galactic medium, through the leakage of Lyman continuum emission, and from shock heating by outflowing material. A systematic analysis of the rest-frame UV spectroscopic of LBGs will help us

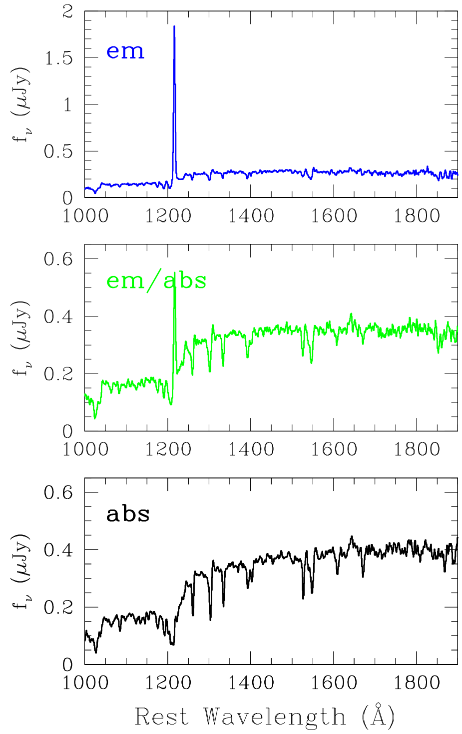

Figure 1. Composite spectra constructed according to Lyman α profile. Each composite spectrum contains more than 200 galaxies, and has a S/N per pixel of ~ 25. The interstellar absorption line strengths increase and the continuum becomes redder with increasing Lyman α absorption strength.

understand how star-formation transforms both galaxies and their surrounding environment at $z \sim 3$.

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